The Smart/Connected City and Its Implications for Connected Transportation

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16. Abstract

This white paper outlines the potential for the emerging connected transportation system to interface with smart/connected cities. Its aim is to lay the foundation for defining steps that the U.S. Department of Transportation (USDOT) Connected Vehicle Program should take to identify and exploit opportunities to help ensure that connected vehicles and connected transportation fulfill their potential to improve safety, mobility, and environmental outcomes in future complexly interdependent and multimodal environments.

The paper describes a framework for understanding the dynamics that animate smart/connected cities: intelligent infrastructure, new knowledge-generating processes, and a smart grid to power it all. In the process, it contextualizes and connects emerging and established concepts that describe technology-enabled changes such as "the sharing economy" and "crowdsourcing."

Drawing on that framework, the paper argues that two trends are likely to predominantly shape the opportunities for connected transportation in future cities: 1) the rise of the Internet of Things and the essential role that vehicles play as nodes in that network, and 2) a transition away from achieving mobility through asset (car) ownership and toward accessing mobility as a service.

The paper concludes by recommending eight research objectives to structure future USDOT research in this area.

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Executive Summary

This white paper describes smart/connected cities and outlines their potential for interfacing with the emerging connected transportation environment. Its aim is to lay the foundation for defining steps that the U.S. Department of Transportation (USDOT) Connected Vehicle Program should take to identify and exploit opportunities to help ensure that connected vehicles and connected transportation fulfill their potential to improve safety, mobility and environmental outcomes in a complexly interdependent and multimodal environment. This paper describes such an environment in terms of a smart/connected city.

In short, a smart/connected city is a system of interconnected systems, including employment, health care, retail/entertainment, public services, residences, energy distribution, and not least, transportation. The system of systems is tied together by information and communications technologies (ICT) that transmit and process data about all sorts of activities within the city.

> *All transportation that helps make a city smart/connected is "connected transportation"—transportation where vehicles, travelers, and infrastructure communicate with each other through various data streams.*

As one of the interconnected systems in a smart/connected city, connected transportation can cooperate with the other systems to provide synergistic benefits. This paper assembles a foundational set of ideas that can begin an effort by the USDOT to identify and maximize these benefits.

To progress toward understanding these potential benefits, the paper explains what is meant by a smart/connected city in chapter 2. The popular press has presented a range of definitions of a "smart city," and they generally revolve around better city management facilitated by advances in ICT. In addition, smart city concepts often but not always involve management goals, such as environmental stewardship, economic competitiveness, or improved quality of life. The term "connected city" is not widely used, but it provides a valuable focus on the data networks that ICT advances make possible. In this paper, we use the term smart/connected city to link to the common discourse about cities, which uses the term "smart city," while using "connected" to emphasize our interest in the data networks that make smart/connected cities structurally different from their predecessors.

The dynamic structure of a smart/connected city differs from that of a traditional city in three major respects. First, smart/connected cities contain and use "intelligent infrastructure," in the parlance of chapter 3: devices and equipment that can sense the environment and/or their own status, send data, and often, receive commands. This intelligent infrastructure connects the city's world of data with its physical reality, creating data based on the real world and following data-based commands to act on the real world as well. Second, smart/connected cities use new analytical processes that have been facilitated by ICT advances. These include big data analysis, crowdsourcing to gather data and solve problems, and gamification to incentivize behaviors and engage the connected citizen. Third, smart/connected cities increasingly require a smart grid—a programmable and efficient electricity transmission and distribution system that responds to dynamic electricity demands. Table ES-1, reprinted from chapter 3, illustrates potential transportation implications of smart/connected cities.

Table ES-1. Linking Aspects of the Smart/Connected City to Connected Transportation

Development	Linkages to Connected Transportation	Policy Implications or Questions
Intelligent Infrastructure: Internet of Things (IoT) and Machine-to-Machine (M2M)	Cars and transit interact with other networked devices, e.g., smartphones, streetlights, traffic control devices, building systems; vehicles can transmit information about state of infrastructure	Operations should identify how to use existing and future data streams from vehicles to identify asset problems and hazards. Need more cross-functional cooperation inside and out of State DOTs for interfacing transportation with IoT.
Process Innovation: Big Data Analytics	Predicting unsafe commercial operators; predicting crashes and congestion; awareness of traveler behaviors across all modes and of real-time travel demands	State DOTs can do more with less, targeting probable safety violators, and making more efficient use of existing transportation assets. Need to research how to leverage predictive travel demand information for dynamic demand-side user pricing. Need to break down DOT modal stovepipes to leverage mode-agnostic data streams.
Process Innovation: Crowdsourcing (e.g., Waze, StreetBump)	Superior and real-time knowledge of state transportation network; ability to influence traveler behavior in real time	Are conventional VMS and traveler information programs obsolete? Should state DOTs invest in crowdsourced issue reporting? How should the USDOT leverage public involvement in both tool development and directing capital investment?
Process Innovation: Gamification (e.g., Chromaroma)	Travelers have new reasons and ways to use mass transit; ability to influence traveler behavior in real time; personalized traveler experience	If we can target congestion-causing travelers, how do we change their behavior to improve total system efficiency at a fraction of the cost of system expansion? How do we fund this? Need strong cross-modal cooperation to achieve multimodality, demand-side measures, and mode shift.
Smart Energy Management	Vehicle-to-grid electric vehicles will be an integral part of the electricity system; V2G vehicle locations and state of charge will be critical to plan and track	Need cross-functional cooperation with the Department of Energy and the Federal Emergency Management Agency, e.g., to integrate planning of roadway sensors, electric infrastructure, and hazard mitigation plans for power grid failures.

As connected transportation interacts with the other parts of a smart/connected city, two trends emerge that will likely shape future opportunities for connected transportation:

1. Connected vehicles and travelers will be able to share data with all sorts of equipment, not only transportation-related devices and infrastructure, as they become integrated into the Internet of Things. (See section 4.1.)
2. Travelers will increasingly be able to procure mobility as a service, rather than purchase vehicles or make other long-term commitments to particular modes of travel. (See section 4.2.)

To harness the potential of connected vehicles in smart/connected cities, given the underlying dynamics and emerging trends noted above, this paper recommends structuring future research around eight objectives:

1. Identify how cities (of all sizes) and city agencies (of all types) can harness the power and potential of connected vehicle data, technologies, and applications and leverage these effectively and efficiently to help achieve mobility, economic, social, and other goals.
2. Explore how cities and city agencies might leverage the opportunities presented by Internet-connected mobile communications technologies—and the data they collect and generate—to connect to citizens, influence traveler behavior in the short and long term, and affect public policy and decision-making.
3. Identify the implications of shared-use mobility, mobility-on-demand, and mobility rightsizing on driver behavior and the changing socio-economic views of driving and mobility.
4. Identify how connected vehicle data can be integrated with a wide variety of other data to create the most effective, innovative, and informative real-time (and predictive) data visualizations to support effective and efficient decision making by a variety of public agencies and also by connected travelers.
5. Identify the most effective crowdsourcing, gamification, and incentivization strategies and applications to address and solve transportation issues/problems and explore how connected vehicle data, technologies, and applications can contribute to support agency and traveler needs.
6. Identify how electric and other alternative fuel vehicles will (or will not) affect mobility decisions in the future (including the economics and purpose of driving), and how these changes might affect the deployment of connected vehicle technologies and applications.
7. Evaluate the benefits of connected vehicle technologies and applications at three levels—overall societal impacts, advancement of cities' particular missions, and personal financial savings—within an overall framework of integrated city activates and services.
8. Identify core stakeholders/partners in the public and private sectors to develop strategies and best practices to leverage connected vehicle technologies, data, and applications, and push forward the state of the practice and the state of the art.

The research team anticipates that USDOT will work with traditional transportation partners and reaching out to representatives of other industries to pursue these objectives. The ultimate goals of federal research in this area are to advance the state of the practice in connected transportation and foster the institutional cooperation that will help realize the full potential of emerging connected vehicle technologies within the smart/connected city environment.

Chapter 1 Introduction

This white paper describes smart/connected cities and outlines their potential for interfacing with the emerging connected transportation environment. Its aim is to lay the foundation for defining steps that the U.S. Department of Transportation (USDOT) Connected Vehicle Program should take to identify and exploit opportunities to help ensure that connected vehicles and connected transportation fulfill their potential to improve safety, mobility, and environmental outcomes in a complexly interdependent and multimodal environment. This paper describes such an environment in terms of a smart/connected city.

In short, smart/connected cities are a system of interconnected systems, including energy distribution, employment, health care, public services, retail/entertainment, residences, and not least, transportation.

> *All transportation that helps make a city smart/connected is "connected transportation"—transportation where vehicles, travelers, and infrastructure communicate with each other through various data streams*.

As one of the interconnected systems in a smart/connected city, connected transportation can cooperate with the other systems to provide synergistic benefits. This paper assembles a foundational set of ideas that can begin an effort by the USDOT to identify and maximize these benefits.

The paper takes an incremental approach in exploring the relationships between connected transportation and other systems in a smart/connected city and outlining the potential opportunities.

- Chapter 2: "What is a Smart/Connected City?" begins by describing or defining the smart/connected city in terms of its essential characteristics.
- Chapter 3: "What Makes a Smart/Connected City Work?" describes the moving parts and dynamics underlying a smart and connected city. Rather than focusing entirely on connected transportation implications and connections, this chapter takes a more holistic approach, to help lay the groundwork for Chapters 4 and 5.
- Chapter 4: "What Roles Will Connected Transportation Play in Connected Cities?" describes two emerging trends that have the potential to transform the role of connected transportation within smart/connected cities.
- Chapter 5: "Conclusions and Recommendations" draws conclusions from the preceding chapters and identifies research questions whose answers will guide USDOT interest and possible activity in smart/connected cities.

Chapter 2 What Is a Smart/Connected City?

Connected vehicles will operate in a connected city. Any benefit to be derived from using connected vehicle technology and data must be understood in this context. The objectives of this chapter are to:

- Define the term smart/connected city as it relates to smart city concepts, and
- Explain why the concepts underlying the connected city have become increasingly relevant.

This chapter provides a foundation for chapters 3 and 4 that explore the connected city's elements, their relationship to each other, and their relationship to connected transportation.

2.1 Definitions

Numerous terms have been used to describe the changes taking place in our cities and lives that have been driven and facilitated by technological change. IBM terms the direction and goal we are heading toward "Smarter Cities," while Cisco talks about "Smart + Connected Cities" and the "Internet of Everything." The editors of *Wired Magazine* write about the coming "Programmable World." This section of the paper describes multiple versions of the most popular term, smart cities, and then describes the connected city as a subset of a smart city.

2.1.1 Smart City

By some accounts, the phrase "smart city" was coined in the early 1990s to illustrate how urban development was now turning towards technology, innovation, and globalization [1]. Others have suggested that the phrase's popularity rose out of the "Smart Growth" movement of the late 1990s, which advocated improved urban planning. Advocates suggested the use of information technology to meet urban challenges in the new global knowledge economy. In the past decade, the phrase has been used by various technology companies (e.g., Cisco, IBM, or Siemens) "for the application of complex information systems to integrate the operation of urban infrastructure and services such as buildings, transportation, electrical and water distribution, and public safety" [2].

There is no single consensus definition of a smart city, but there is some agreement that a smart city is one in which information and communication technology (ICT) facilitates improved insight into and control over the various systems that affect the lives of residents. Table 2-1 lists a range of definitions, with the ICT elements highlighted in bold.

Table 2-1. Smart City Definitions

Source	Definition
Courtney Humphries, Boston Globe	… *A wired, sensor-filled streetscape that uses cloud computing and sophisticated software* to transform cities into intelligent machines that adapt to people's lives and steer behavior… The ultimate vision is a city that is hyper-efficient, easy to navigate, and free of waste—and which is *constantly collecting data* to help it handle emergencies, disasters, and crime [3].
Anthony Townsend, New York University	A city where *information technology* is being incorporated into services that affect urban problems [4].
Gridaptive Technologies, transportation and power systems manufacturer	A technology term that is inclusive of *smart grids, smart meters, intelligent transportation, buildings, and other smart infrastructure* that make up technologically innovative cities [5].
Colin Harrison, IBM	A city that has "*Urban Systems models* that are capable of helping citizens, entrepreneurs, civic organizations, and governments to see more deeply into how their cities work, how people use the city, how they feel about it, where the city faces problems, and what kinds of remediation can be applied" [2].
Boyd Cohen, Fast Company Co.Exist	…a broad, integrated approach to improving the efficiency of city operations, the quality of life for its citizens, and growing the local economy [6].

The list shows near unanimity (in this very small sample) about the central role of ICT. The last entry is a notable exception, being more focused on the ends—efficiency and quality of life—rather than the means. This view of a smart city is illustrated in

Figure 2-1, which shows various strategies and approaches as spokes on a wheel, with intermediate goals on the inner ring and the resulting smart city at the core. The wheel shows that ICT is a factor contributing to a smart city, but not the defining enabler.

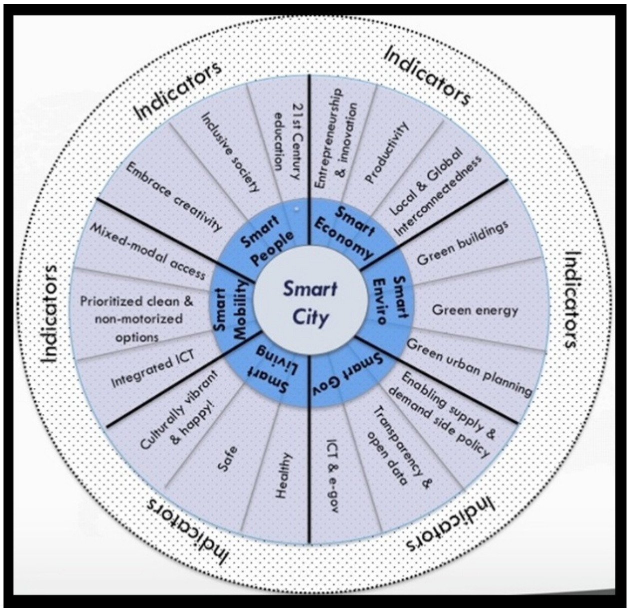

Figure 2-1. Smart Cities Wheel (image source: B. Cohen [6])

Other visions of smart cities include both goals to be achieved and technology as part of the solution as well. The Smart Cities Council, which includes technology companies Cisco, IBM, General Electric (GE), Microsoft, Qualcomm, and others, uses three terms—livability, workability, and sustainability—on its masthead and to define its brand. From its home page:

> *With staggering population growth on the rise, it is essential that our cities allow future generations to not only sustain but thrive. We envision a world where digital technology and intelligent design are harnessed to create smart,* **sustainable** *cities with* **high-quality jobs** *and* **high-quality living** *[7]. (Emphasis added.)*

The implication here is that environmental sustainability and a high quality of life are intrinsic to being a smart city.

2.1.2 Connected City

In contrast to the term "smart city," the term "connected city" implies a focus on the electronic, physical, and even human infrastructure, the network of connective tissue that helps make the city work. Whereas smart city concepts generally include both means—ICT and other enabling strategies and approaches—and ends, the concept of a connected city is more focused on the networks that provide a certain capability to gather, exchange, and use data and information. The distinction is evidenced by Cisco's use of both "smart" and "connected" in marketing its city management services.

This paper will use the term "smart/connected city." This is with the understanding that:

- A connected city is one where all relevant city systems—transportation, utilities, employment, health care, public safety, education, and others—are capable of communicating with each other to allow coordination and reduce waste.

- A smart city is one where the government and citizenry are using the best available means, including ICT, to achieve their shared goals. This often includes economic development, environmental sustainability, and improved quality of life for citizens.
- To be fully "smart," a city must be "connected."
- It is more natural and aligned with its traditional mission for the Intelligent Transportation Systems Joint Program Office (ITS JPO), which is sponsoring this exploratory research, to focus more on the capability implied by the term "connected city" than on the result implied by "smart city."
- Governments and the businesses that seek to sell services and equipment to them speak in terms of "smart cities." Including "smart" in this paper's term helps link to the larger dialogue.

2.2 Smart/Connected City Examples

There are several examples of smart cities throughout the world. Due to the disparate elements a smart city might contain, the kinds of applications used are broad and varied. Few cities can yet be called wholly "smart," but some of the most advanced use global best practices that should be models for others. The four foreign cities highlighted below provide a glimpse at the potential of smart city approaches; the American examples indicate best practices among U.S. cities.

Rio de Janeiro, Brazil **|** Rio contains the largest "smart" operations center in the world, aggregating information from 30 agencies under one roof. The center was conceived after Rio experienced a devastating landslide in April of 2010; the disaster led Mayor Eduardo Paes to contact IBM to learn whether big data could aid in predicting and responding to future disasters. The project soon expanded from predicting landslides into the operations center of the City of Rio. The center became the first of its kind, analyzing historical and real-time data to more efficiently manage multiple city services [8][9]. In addition to improving its management of traditional data streams, Rio is also accessing crowdsourced data. Rio is the first city to collect data from drivers by partnering with the mobile application for road navigation, Waze, as well as transit users and pedestrians by partnering with the transit navigation mobile application Moovit. It is also talking with the mobile application for cyclists, Strava, about accessing its data [10].

Santander, Spain **|** Santander is a living experimental laboratory city, with 10,000 sensors located around downtown. They are attached to street lamps, poles, and building walls, and buried beneath the asphalt of parking lots. These sensors collect data on traffic, environmental factors, weather, and people, among other things. A smartphone application makes the data available to citizens, providing real-time transit information, cultural event schedules, tourist and sightseeing information, and retail offers. Future plans are to incorporate more data, including information on demographics and real estate, with further online "village square" applications. This innovation promises to have positive impacts on the local economy and increased tourist accommodation [11].

Singapore **|** Singapore has rapidly become one of the world's leading cities, and proponents attribute its success to its efforts to become the world's smartest city. With new data intake throughout the island's systems, information can be tapped for a plethora of applications. Singapore's Land Transport Authority is working with IBM and the Massachusetts Institute of Technology (MIT) to improve public transit use [12]. Singapore's Infocomm Development Authority has established a Smart Cities Programme Office, and its initiatives are apparent throughout the city. Sensors, cameras, and global positioning system (GPS) devices provide information on traffic, even predicting future congestion and recommending alternate routes. Singapore was the first city in the world to implement congestion pricing, which uses traffic data to adjust toll pricing in real-time. Ninety-five percent of residents and businesses have access to a super-fast, next-generation broadband connection. Drawing on its successes, Singapore is now working with China to develop a smart city patterned after Singapore's systems [13].

Songdo, South Korea **|** the City of Songdo, slated for completion by 2015, has a ubiquitous information network underpinning the city, with energy use and other essential city services monitored and in some cases controlled by city officials, using algorithms to provide efficiency. This network in turn provides citizens with tools such as video conferencing and a (non-identity linked) smartcard that acts as an integrated credit card, access pass, and house key. Almost any device, building, road, or transit vehicle will be equipped with wireless sensors or microchips. All the data will be collected, analyzed, and monitored in real-time by the central monitoring hub, providing valuable insights into how people work, live, and think within a smart city [14][15].

Los Angeles **|** Perhaps following Rio's model, Los Angeles attempted to use computer algorithms to predict the location and effects of earthquakes and aftershocks [16]. Although predicting earthquakes was not possible, researchers were able to predict aftershocks, enabling effective evacuations of potentially affected areas. Researchers also found that the algorithm to predict aftershocks could be used to predict criminal activity. This idea gave birth to PredPol (Predictive Policing), a computer-based program that determines potential crime areas. After using PredPol in a test neighborhood of Foothill, officials found a 13 percent decrease in crime during the first four months due to an increased police presence in potential crime areas [17].

Boston **|** The City of Boston has established an Office of New Urban Mechanics to find innovative solutions to city problems, and many of those solutions involve information technology [18]. Beyond that purpose-oriented office, many Boston agencies have been proactive in using new ICT tools [3]:

- Smart Parking is an application used to decrease vehicle idle time while parking.
- ShotSpotter, used by the Boston Police Department, determines the location of gun shots.
- Smart Rapid Transit involves closely monitoring subway stations via video cameras as well as sensors that detect movement as well as the presence of biological weapons.
- GHG Emission Tracking uses sensors on top of high-rise buildings to track and detect greenhouse gas emissions.
- StreetBump is a mobile application that uses cellular phones to determine the location of potholes.

2.3 Enablers

There are a number of narratives explaining why the smart/connected city framework has become important, and a survey of literature suggests that evolution in technology is the main explanation. In very broad strokes: in the past few decades, a new data-based system has developed. The Internet provides the main data conduit, transmitting large volumes of sensor data at near light speed. Wireless communications technologies such as cellular phone systems, Wi-Fi, and Bluetooth create a field of data connectivity throughout much of the industrialized world. Smartphones, mobile computing technologies, and most recently, remotely programmable machines, make up the interface between the data-based system and the physical world. Chapter 3 describes the parts of the data creation-transmission-use network in more detail.

As the data network has evolved, society has also changed in ways that have enabled and accelerated the use of data. People who have grown up with computers and the Internet—often termed "digital natives"—make up an increasing proportion of the workforce and society at large. Because they are more comfortable with ICT and mobile ICT, they tend to accept and even demand that it be integrated into their lives [19]. Also, partly because of an aging population that is less mobile and less demanding of space than it was when it was younger, the trend is for a growing fraction of people in the U.S. and also globally to live in urbanized areas [20]. These urbanized areas offer greater opportunities for the creation and use of data, as multiple people and systems interact more frequently than in more rural areas.

2.4 Summary

Connected and smart cities differ from earlier models of city and society largely in that they rely heavily on ICT to achieve their goals more efficiently. The smart/connected city model is important now mostly because of the evolution of ICT over the past few decades. The trajectories of ICT and other supporting factors, such as urbanization rates, suggest that smart/connected city concepts will become more important in the future.

Chapter 3 What Makes a Smart/Connected City Work?

How will connected vehicle technologies interact in this smart/connected city environment? This chapter takes the next step in answering the question. The objective of this chapter is to describe the trends and technologies that interact to constitute a smart/connected city. Although the chapter includes connected transportation examples, it does not focus on connected transportation, but aims to paint a holistic picture of how a smart/connected city operates, to make it easier to identify possible linkages among different systems and sectors of the economy in chapters 4 and 5.

This chapter describes the increasingly data-based system of systems that underlie a smart/connected city. The first section on intelligent infrastructure discusses the interface between the physical and data worlds, where devices capture data from the physical world and act on it based on commands and programming. The second section on process innovations lays out some critical new ways that data becomes knowledge and action in a connected city—big data, crowdsourcing, and gamification. The third section on smart energy management describes an evolution in energy distribution that supports the intelligent infrastructure.

Before describing the smart/connected city elements in more detail, we need to briefly discuss ICT, which is the primary enabler of them all. It is beyond the scope of this paper to catalog the advances in ICT that make smart/connected cities possible, but a few points of information are useful. First, smartphones and other mobile devices are critical to the data system, and they are projected to grow in market share: predictions are that they will make up two-thirds of the cellular phone market by 2017 [21]. Second, the other critical element of ICT, mobile and fixed-line data transmission infrastructure, has expanded in bandwidth recently and is projected to continue. Because the equipment needed for data capture and use everywhere is growing more and more capable, the systems described below will likely become more sophisticated and more common over time.

3.1 Intelligent Infrastructure

Intelligent infrastructure describes the integration of sensors, networked communications, and computing hardware and software into physical infrastructure. These enhancements to traditional infrastructure of all types have sparked a rapid evolution, and the transportation industry is no exception. Infrastructure—from homes to bridges to pipelines to streetlights—that was previously “passive” is becoming controllable or self-controlling, imbued with analytic ability, and able to communicate with other infrastructure elements and humans [22]. Crucially, because intelligent infrastructure components are connected to the Internet, they can often be made to work together—to collect multi-source, contextual data, and to carry out integrated functions [23]. These capabilities make intelligent infrastructure more cost-effective than its traditional counterparts, as well as significantly more useful and adaptable.

Intelligent infrastructure is rapidly becoming pervasive. Variously also called the “Internet of Things” or “The Programmable World,” among other terms, this concept denotes a world in which our built infrastructure is linked and dynamic, often displaying intelligence via integrated sensors and adaptive controls. For example, raised pavement markers (e.g., reflective dots), which until recently have been among the simplest and "lowest tech" pieces of infrastructure, are gaining intelligence. In the United Kingdom, the Intelligent Renewable Optical Advisory System (INROADS) is developing pavement markers (studs) that incorporate LED (light-emitting diode) lighting, sensors, microprocessors, and wireless communication capabilities. Powered by built-in photovoltaic cells and/or piezoelectric panels (which generate electricity when a passing vehicle drives over the marker), these smart studs could have a range of applications. For example, they could detect vehicles and pedestrians at intersections, and illuminate to warn of danger. Smart studs could illuminate the outlines of dangerous curves on rural roads for each passing vehicle, then power down between vehicles to conserve energy. Similarly, smart studs could light up to mark lane geometry for vehicles entering complex intersections [24]. Applications in other areas of transportation, energy conservation, health care, and food distribution are also available.

Two key enablers of the development of intelligent infrastructure are "smart objects," and machine-to-machine (M2M) communication.

3.1.1 Smart Objects

As the *New York Times* puts it: "Already billions of processors are embedded in our smartphones, cars, appliances, buildings, and the environment. These sensors can send out streams of data about their surroundings…." [25]

As sensors, microprocessors, and wireless networking components become ever smaller and cheaper, the result is that almost any object can collect, send, and receive data. Furthermore, thanks to rapid advances in data storage and computer power, the flood of data from this ever-expanding universe of sensors can be productively analyzed, often in real-time, better than ever before. Since the sensors in question are part of physical objects, we can use our newfound knowledge to exert greater control on the physical world. In other words, "…computing will have evolved from merely sensing local information to analyzing it to being able to control it. In this evolution, the world gradually becomes programmable" [25].

The home automation industry provides a good example of this trend. Familiar home infrastructure elements, such as lighting, heating, and door locks can be fitted with network connections and programmable controls. Additionally, networked video cameras, fire/CO detectors, and other types of sensors enable the homeowner to monitor the home remotely. On a more mundane level, networked power outlets that plug into existing wall receptacles allow any existing appliance to be networked and remotely controllable. Smartphone applications make control and monitoring easy.

The dramatic growth in consumer-oriented smart objects in recent years could create the impression that the consumer electronics market is driving the smart object industry, when in fact consumer devices are relative latecomers. Numerous commercial and industrial sensor applications—truly "intelligent *infrastructure*"—predate the introduction of smartphones and other sensor-enabled consumer devices. Commercial agriculture, for example, has been in the vanguard of sensor use for many years. By the early 2000s, there was already a burgeoning market for wireless agricultural sensors. For example, there was growing demand for applications that allow farmers to monitor crop and field conditions, fertilizer application, and production by exact location [26].

Sensor sales across all markets worldwide have been strong, growing from 4.1 billion units ($2.7 billion) in 2008, to 7.7 billion units ($4.8 billion) in 2011 [27]. (See

Figure 3-1.) According to the Semiconductor Industry Association, in 2012, the worldwide sensor market was worth $8 billion, and it is projected to grow 4.5 percent in 2013, and 7.1 percent in 2014 [28]. Other forecasts indicate similar growth trajectories [27].

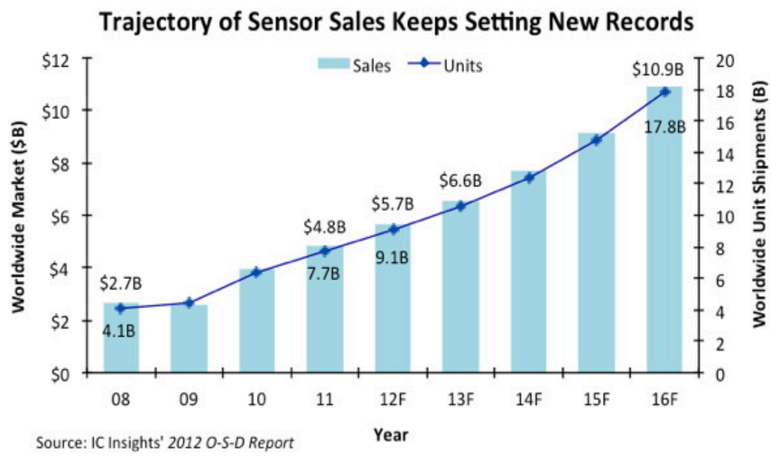

Figure 3-1. The Dramatic Growth in Sensor Sales [27]

3.1.2 Machine-to-Machine (M2M) Communication

The vital corollary to objects getting smarter is that they are also, increasingly, able to communicate with each other. Machine-to-machine (M2M) communication is not new; it began almost two decades ago, using now mostly defunct private networks that enabled basic monitoring and control functions to be carried out remotely for certain infrastructure elements. The Internet quickly supplanted private networks, lowering the cost and simplifying the deployment of M2M applications. In theory, every object could have its own Internet Protocol (IP) address. One potential limiting factor for this vision is the supply of unique addresses. The current stock of approximately 4.3 billion IP addresses, generated via Internet Protocol Version 4 (IPv4) is nearly depleted [29]. Fortunately, development of the successor protocol Internet Protocol Version 6 (IPv6) has been underway for several years, and will solve the IP address supply problem. IPv6 offers "enough potential Internet addresses to give every atom on the face of the earth its own address" [30].

From the perspective of public infrastructure management, an important aspect of M2M communications over the Internet is that networked objects have from the beginning been designed and deployed following the "federated" model familiar in the development of information systems architectures. Federation allows for interoperability and information sharing among semiautonomous, decentralized systems, and applications [31]. For physical infrastructure, federation means that:

> *. . . New network-friendly devices . . . are able to set, define, install, and debug themselves. In the case of infrastructure, gas valves, telecommunication switches, traffic signals, and other devices could be added to the infrastructure system at any time. The infrastructure management system will be able to recognize them immediately and start passing orders and receiving data from them [32].*

A relatively recent development in intelligent infrastructure illustrates the value of combining M2M with "smart object" capabilities. Intellistreets [33] is a company developing "intelligent" lampposts—streetlights that incorporate wireless networking (among all lampposts on a network, with cloud-based servers, with emergency-response centers such as police stations, and with other applications); adaptive lighting (to conserve energy); communications capabilities (audio and visual display); digital street signs; and the ability to support cameras and environmental sensors such as gas-leak detectors, seismic monitors, and flood detectors. The smart lampposts can be integrated into larger public management systems. For example, during road construction the lampposts could be remotely programmed to change their digital street signs to display detour notices and to guide motorists via sequenced, flashing lights, while integrated cameras allow staff at the transportation management center to monitor traffic. In the event of a violent event such as a gunman in an office building, lampposts on the perimeter of the area could flash red and give emergency announcements while integrated cameras enhance police visibility of the area.

3.1.3 Internet of Things

The growth and evolution of smart infrastructure comprises an incremental set of developments. First, as technology costs continue to drop, more and more objects will acquire intelligence via integrated sensors, processors, and wireless transmitters. Second, the devices will be networked in a federated model, enabling flexibility and scalability. Third, M2M (along with the appropriate software) will enable smart infrastructure elements to rely on each other to coordinate actions.

This concept of semiautonomous, networked objects has been dubbed the "Internet of Things" (IoT). IoT is a concept industry analysts, futurists, and numerous science fiction books and movies have been forecasting for decades. Many forecasts have been narrowly focused on consumer-facing applications—from pet trackers to remote car starters—that pair smartphone apps with IoT-enabled devices. Such examples are intriguing, but fall far short of the full potential of the IoT. Other examples are more compelling because they demonstrate how the IoT makes use of big data to provide contextual awareness for improved resource management. For instance, in the freight rail industry, "[c]omputers pull GPS data from railway locomotives [such as] the weight and lengths of trains, the terrain and turns, to reduce unnecessary braking and curb fuel consumption by up to 10 percent" [34].

Various other infrastructure system elements could have similar influence. Whether it is traffic signals that are entirely coordinated and can be dynamically controlled [35], parking that prices itself based on demand to optimal usage [36], or networked street lights that sense the presence of people or autos as noted above, the ability of intelligent infrastructure to impact the world is clear.

Recent market forecasts for the IoT from component manufacturers and industry analysts all predict dramatic growth in the coming years. For example, both Cisco [37] and Ericsson [38] predict at least 50 billion Internet-connected devices in use worldwide by 2020. The McKinsey Global Institute estimates the potential economic impact of the Internet of Things to be $2.7 trillion to $6.2 trillion per year by 2025, with the largest impacts in health care and manufacturing [39]. (Together, urban infrastructure and vehicles—an approximation of total transportation impacts—make up $0.15 to $0.35 trillion of the total.)

3.1.4 Challenges: Privacy and Security

The Internet of Things is a world where anything with intelligence will have an online presence, generating rich, contextual data that could be put to uses currently perhaps unimagined. The value of these possibilities rests on systems that measure, track, and analyze more about our world than ever before. The new volume and variety of data creates new privacy risks.

For example, a system called Presence Orb uses sidewalk trash compactor bins that can capture the media access control (MAC) address of nearby smartphones to measure pedestrian movements [40]. There is a range of productive uses of that data, from real-time transportation and event planning to marketing to road and sidewalk design. However, MAC addresses are linked to individual devices, creating a risk of privacy invasion. To reduce that risk, version 8 of Apple's operating system for iPhones, iOS, scrambles MAC addresses on its devices [41].

Alongside private sector initiatives to insulate particular devices from privacy risks, the public sector is responding with its own approaches.

- In 2012, the Obama Administration released the Consumer Privacy Bill of Rights, which clarified consumers' rights related to collection, transparency, respect for context, security, access and accuracy, and individual control over personal data collected. As with essentially all other U.S. privacy initiatives, it is aligned with the Fair Information Practice Principles (FIPPs) embodied in the Privacy Act of 1974 [42].
- In May of 2014, the courts of the European Union (EU) established a "Right to be Forgotten" under the EU's 1995 Data Protection Directive. It allows individuals to insist that search engines remove links to erroneous or excessive personal information [43]. The EU has proposed regulations to enforce the courts' findings.
- Also in May 2014, the Obama Administration released a report on big data, privacy, and security. It recommends advancing and enacting into law the Consumer Privacy Bill of Rights, updating the Electronic Communications Privacy Act, legislating a national standard for data breaches (a security issue), and other initiatives [42].

IoT security concerns are perhaps even more serious than the above privacy concerns. Even with complete and full privacy regulations, security will remain an issue as the proliferation of networked objects means that there will be vastly increased opportunities for hacking and other threats, in places where they never before existed. IoT devices currently on the market, such as 'smart' refrigerators, have been found to contain inadequate software allowing outsiders to easily hack the device and obtain an outlet into a secure home network. Other devices such as home security cameras were found to have an absence of a platform or interface for proper security: allowing outsiders to easily hack into the unsecure video. A study by the University of Washington found that the software in many common connected devices, such as car devices, medical devices and children's toys made them susceptible to hacking [44].

An important aspect of IoT devices is that, due to their presence on the Internet, IoT objects are detectable. In fact, there exists a search engine specifically designed to find IoT devices, Shodan, which crawls the Internet to catalog connected devices. Users can search this catalog and discover the IP address, geographic location, and characteristics of each device, including whether it is password protected.

> *Countless traffic lights, security cameras, home automation devices, and heating systems are connected to the Internet and easy to spot. Shodan searchers have found control systems for a water park, a gas station, a hotel wine cooler, and a crematorium. Cybersecurity researchers have even located command and control systems for nuclear power plants and a particle-accelerating cyclotron by using Shodan [45].*

Shodan illustrates the critical importance of addressing IoT security comprehensively—from passwords, to firewalls, to considerations of whether certain devices ought not to be connected to the Internet.
As with the privacy issues, both the private and public sectors are responding to security concerns.

- Technology companies have held hack-a-thons in which computer experts are tasked with attempting to hack various security platforms, enabling the companies to identify and eliminate vulnerabilities [46] [47].

- The Federal Trade Commission (FTC) has taken steps to ensure consumer security by requiring companies to explicitly state a lack of security software and platform or to provide the software and platform [44].
- In a related effort in 2014, the Obama Administration established the nonbinding Cybersecurity Framework to help reduce cybersecurity risks to the Nation's critical infrastructure. The Framework is a national standard to identify, assess, and manage cybersecurity risks. Although currently the Framework focuses on critical Internet infrastructure that pertains to the essential security, national economic security, and national public health or safety, the principles can be expanded to IoT devices [42].

National and multinational governments are promising to remain engaged and vigilant on privacy and security issues. The European Commission is weighing alternative regulatory frameworks for both aspects of the IoT [48]. In the U.S., Edith Ramirez, the Chairwoman of the FTC, has indicated that IoT privacy and security implications are areas of concern, and the FTC hosted a workshop on these topics in November 2013 [49]. However, individual protections offered by the EU and the U.S. tend to differ; the extent to which their approaches will converge is an open question [50].

3.2 Process Innovations

In a smart/connected city, data will be more readily available from intelligent infrastructure as discussed above. Determining how to interpret that data is a critical step in creating value from the data and making smart decisions. This section reviews three main themes in the process innovations that drive and inform smart/connected cities:

1. Big data,
2. Crowdsourcing, and
3. Gamification.

3.2.1 Big Data[1]

A fully developed connected vehicle environment will produce vast amounts of information as vehicles and infrastructure send messages to one another. Effective use and management of this data has the potential to transform the transportation industry and transportation in a connected city. "Big data" is a term for a family of techniques and technologies that many businesses are increasingly using to improve and streamline their business practices, and it holds real promise for the management and analysis of connected transportation data.

Big data is an approach to generating knowledge in which a number of advanced techniques are applied to the capture, management, and analysis of very large and diverse volumes of data—data so large, so varied, and analyzed at such speed that it exceeds the capabilities of traditional data management and analysis tools. Big data is often discussed in terms of the 3 Vs: unprecedented **volumes** of data, with substantial **variety** in the types of data collected and analyzed at high **velocity**—to enable real-time decision making. Some organizations have defined a fourth V, **veracity**, and even a fifth V, **value**. Regardless of whether one favors a three-, four-, or even five-V definition of big data, the Vs alone are shorthand and leave a lot of questions

[1]This section also appears in another paper produced by the Volpe Center and sponsored by the ITS JPO entitled "Big Data's Implications for Transportation Operations: An Exploration." It is in publication.

unanswered. The following sections describe big data by contrasting it with traditional approaches for data capture, management, and analysis.

Table 3-1 provides a summary. Although the table lays out stark differences between traditional and big data approaches, in practice they lie on a continuum, with the two columns in the table staking out the endpoints. Many cases of analysis will land somewhere in the middle, looking like big data in some aspects and traditional analysis in others.

3.2.1.1 Data Capture

In data capture, there are three defining differences between big data approaches and traditional approaches.

First and most important, big data often involves measuring the behavior of nearly an entire population or system, whereas traditional analysis relies on statistical samples. While traditional analysis is often designed around the conditions that allow valid statistical inference about the characteristics of a population based on measurements on a small sample, big data-style analysis is built around the possibility of learning about systems by observing them in their entirety.

A second and related difference between traditional and big data approaches to data capture is that traditional approaches, because they feature a collection of fractional samples, usually require much more careful planning to ensure that data are captured at the right place and time under the right conditions. Because a small number of observations must be leveraged to provide information about the entire population, those observations carry a lot of weight and must be chosen carefully. Often, preconceived notions of causation guide data collection so that what are anticipated to be the key variables are measured. With big data, knowledge is produced by observing much larger datasets, including the entire system/population; the question of which data to collect is eliminated (or at least deemphasized). An important byproduct of this fact is that data collected for one purpose can often be reused to answer other questions.

A third distinguishing feature of data capture for big data is that the data are often coming from multiple sources and are diverse—including actively or passively crowdsourced data (see section 3.2.2 for a discussion of crowdsourcing) and/or electronic records of other activities incidental to the question at hand, also known as "electronic breadcrumbs." This "multiple source" characteristic of big data is linked to the need for copious data about a population: both crowdsourcing and the "electronic breadcrumbs" are often less expensive than purpose-driven targeted data collection. It is also related to difference #2 above, that data can be repurposed more easily when working with big data.

Table 3-1. Defining Characteristics of Traditional Versus Big Data Approaches

	Traditional Approaches	Big Data Approaches
Data Capture		
Statistical Sampling	**Yes** Small fractions of the populations are sampled	**No** Datasets encompass nearly all of a population
Experimental Design	**Critical** Guided by theories of causation and need for statistical validity	**Less Important** Data collected for other purposes often analyzed to address new questions (repurposed data)
Number of sources	**Limited** Data come from dedicated sampling/collection	**Very Large** Crowdsourced data or “electronic breadcrumbs”—incidental, automatically or system-generated electronic records—often feed analyses
Data Management		
Storage	**Single Physical Location**	**Multiple Locations** Shared or virtual access (cloud)
Structure	**Structured** Data resides in fixed fields	**Structured and Unstructured** Some data not in fixed fields, e.g., video and text streams in addition to structured data
Data Analysis		
Analytical Approach	**Statistics** Traditional regression methods	**Data Science** Pattern recognition and machine learning in addition to traditional statistics
Number of Variables	**Limited**	**Very Large**
Processing	**Manual** People use specific tools and intuition	**Automated** Optimization routines create best-fit models

3.2.1.2 Data Management

Data management for big data is distinctive principally in that it is usually decentralized as a matter of necessity. Big data capture often draws on decentralized data sources, as through crowdsourcing and/or “electronic breadcrumbs,” and collecting and consolidating this data often requires distributed resources. Because of the size of the datasets involved, data handling and analysis are often impractical if limited to dedicated servers, and cloud computing becomes preferable. Finally, the diversity of the data that may be analyzed in big data approaches, including traditional structured databases and unstructured data such as video and text, lends itself to a diversity of data storage sites that need to be connected and collated to allow the analysis to proceed. In the context of transportation operations where various data in a region are collected and physically held by different jurisdictional and modal agencies or departments, big data necessarily implies data sharing among agencies. Big data techniques like cloud computing and federated data systems help address this challenge.

3.2.1.3 Data Analysis

When dealing with big data, datasets of interest often contain huge numbers of variables and vast numbers of data points. Traditional statistical methods are often insufficient and unsuitable for reliably gleaning information from such diverse datasets, and traditional data handling techniques, such as SQL (Structured Query Language) databases, are often not up to the task of handling the volume. Instead, it is necessary to use a family of approaches referred to as "data science," which encompasses a number of fields including advanced statistics, signal processing, machine learning, and pattern recognition [51]. To handle the volume of data, data science must be coupled with data handling techniques suited for large datasets such as distributed computing.

3.2.1.4 Examples

Big data analytics are in wide use across various industries.

Insurance Fraud Detection: GE suffers fraudulent claims against its warranties on home appliances. The company's traditional method of detecting fraudulent claims is to compute 26 metrics for each claim (e.g., time to end of the warranty) and refer the claim to an auditor when multiple metrics fall outside acceptable ranges. One limitation of this claim-by-claim approach is that it is impossible to discern patterns emerging in the incoming claims. After instituting a big data approach looking across all aspects of all claims, GE estimated that it saved $5.1 million in the first year [52].

Predicting Mechanical Failure: United Parcel Service (UPS) uses big data analytics to reduce its maintenance costs. Because on-the-road vehicle breakdowns tend to be expensive and disruptive to its operations, UPS used to replace certain parts on its trucks every two to three years. However, this led to the replacement of perfectly good parts; the simplistic maintenance plan was wasting money. Starting in the early 2000s, UPS began to use predictive analytics to identify those parts that were in fact nearing failure and in need of replacement. Equipping the vehicle undercarriage with an array of sensors, UPS identifies patterns in the sensor readings that corresponded with part failure. Armed with a fleet of sensor-equipped vehicles and knowledge of the patterns that presage failure, UPS is now able to predict part failures and replace parts only as needed [53].

Market Segmentation: Netflix estimates that 75 percent of its viewers' activity is guided by recommendations that it provides. Its recommendation engine is an algorithm fed by and based on a stream of disparate data. An essential part of that data is a video code catalog, wherein different movies and television shows are classified according to a wide range of categories (over 76,000 categories as of late 2013 [54]): release date, director, and many others. User behavior is critical to the matching algorithm: the company tracks what a user watched, searched for, and rated, as well as browsing and scrolling behavior [55].

Big data describes the process by which previously impossible insights can be extracted from the huge volumes of diverse data that are becoming increasingly available. As such, it points toward the possibility of managing the various, interconnected systems within a connected city more efficiently and synergistically than we can foresee.

3.2.2 Crowdsourcing

While big data provides a machine-centered approach to improved data use, crowdsourcing is a more person-centered path to the same goal. Crowdsourcing refers to "the practice of obtaining needed services, ideas, or content by soliciting contributions from a large group of people and especially from the online community rather than from traditional employees or suppliers" [56]. That is, it is an approach to value generation that draws on inputs from groups of generally unknown individuals.

The mobile navigation application "Waze" relies on multiple forms of voluntary user input—crowdsourced data—to generate real-time traffic alerts, route suggestions, and estimated times of arrival. In the least intrusive form, users consent to have their location tracked as they drive with a one-time click; in return they get access to the service's alerts and predictions for as long as they use the service. This style of data crowdsourcing could be termed "passive crowdsourcing." At the next level, users can connect to friends through Facebook and share their driving experience. By choosing to involve Waze in their Facebook life, users make it easier for Waze to mine their social media entries for useful data. In the most direct form of engagement with Waze, users can choose to post information for other users' use, such as reports traffic incidents or local gas prices; in exchange, they users earn points with which they can "buy" specialized avatars that represent their vehicle on the virtual map, which other users can see [57]. Gathering crowdsourced data in this way, relying on users to directly input it, could be termed "active crowdsourcing."

Crowdsourcing has also become a common way of generating ideas or solutions to problems. For example, in 2010, the General Services Administration launched Challenge.gov, which is a platform for Federal agencies to host competitions. Since then, 58 agencies have run 288 challenges through the site [58]. The site was modeled on private sector challenge hosting websites, presumably because of their popularity and success.

Crowdsourcing is important to the concept of the connected city because it provides a low-cost approach for collecting data and insights from willing participants. As the Waze example illustrates, multiple forms of crowdsourcing can allow connected travelers to work together to create a fairly holistic picture of traffic issues and options. There are undoubtedly other possibilities for crowdsourced data to improve connected transportation as well.

3.2.3 Gamification

Gamification refers to the application of game design principles to non-game activities, incentivizing user engagement by appealing to a sense of fun and competition. The approach often involves awarding points and badges or comparable status symbols for good performance. Competition is often encouraged through leaderboards or some other means of performance comparison [59]. Examples include the following:

> Microsoft convinced many customers of its Office productivity suite to learn its new, ribbon-based menu structure (which up until then had been essentially unchanged for over a decade) by creating a game: Ribbon Hero 2. The game offers levels that mark the gamer's experience and skill, with each level providing new challenges in the use of Excel, PowerPoint and the rest of the Office family [60].
>
> Foursquare is a location-based social networking service that uses game elements to gain popularity with its users and make the service more valuable to sponsors. Foursquare users can earn points and badges by "checking-in" at locations, including retailers and restaurants. For users, the benefit of being tracked by Foursquare and checking-in is to gain retail specific coupons, arrange to meet friends who also use the service, and become the mayor of a location by checking-in more than other users. At the same time, this user location and activity information is enormously valuable to Foursquare and its sponsors, who can use it for market analysis and targeted advertising [59].
> Chromaroma is a location-based online service in London that encourages travelers to use all sorts of alternative transportation [61]. The core of its approach is a game that allows London's commuters to gain points for themselves or a team by using public transportation, walking, and biking, or by visiting certain check-in locations. The person or team with the most points at each location is considered the

leader until dethroned. Players can also receive points by completing missions, which are often designed to distribute ridership equally among transit options. The service also encourages users to share their travel activities with their social networks [62]. It includes many game elements: competition, cooperation, and the status that comes with achievement. As with Waze, it requires users to provide their location data to a back-office system. As James Burgess notes in *Thinking Highways*, it also offers a means for transit system operators to encourage behavior that benefits the system overall:

> *It is easy to imagine Chromaroma being an important part of the travel management plan around a big event. It has unique potential to personalize [sic] travel information for individual travelers – "You are trying to travel through Kings Cross station as often as possible. Watch out for the (disruption or special event) on Wednesday!" Challenges and rewards could be used to draw travelers away from busy stations or dangerous incidents [62].*

Gamification facilitates knowledge generation process by encouraging broad user participation in activities that generate useful data at low cost. It can also be valuable in encouraging people to act in a way that advances the goals of a company or government agency. For example, transportation agencies may be able to use gamification to actively respond to traveler demand and affect their choices.

3.3 Smart Energy Management

This section describes two related innovations in electricity distribution and management. First is the "smart grid," which is the natural extension of intelligent infrastructure technologies and practices to the realm of energy. The smart grid unlocks efficiencies when appliances, buildings, and power plants are networked to make automated decisions. Second, electric vehicles (EVs) create new needs for energy availability and also the potential for new flexibility in energy storage and demand shifting.

3.3.1 Smart Grid

The emerging "smart grid" infrastructure integrates ICT into the electrical power grid to sense and intelligently act on real-time energy flow information, making it possible to greatly improve the efficiency, reliability, and sustainability of the electricity system. By dynamically allocating building-scale as well as commercial-scale power generation, the smart grid is making possible the growing share of intermittent power sources such as wind and solar.

According to Cisco, the smart grid will ultimately eclipse the size of the Internet:

> *Our expectation is that this network will be 100 or 1,000 times larger than the Internet. If you think about it, some homes have Internet access, but some don't. Everyone has electricity access—all of those homes could potentially be connected [63].*

Other companies, including IBM, Intel, and many startups, are ramping up smart grid efforts to capitalize on expected investments from utilities and federal and state governments. Smart meters in a person's home, for example, can already communicate energy usage to utilities in near real time. Targeting this smart grid building block, the Obama Administration set a target of 40 million smart meters in U.S. homes by 2015 [64].

In the future, real-time sensing and digital communication may allow both utilities and consumers to manage the electricity supply more efficiently. Using sensors or an embedded router in a substation, a local utility can send information about demand in real time to power generators as well as send automatic low power commands to customers' appliances and automated building systems. That will allow generators to run more efficiently and to incorporate larger quantities of intermittent wind and solar power.

Several ongoing challenges exist to full development of smart grids in the U.S. and globally. For one, to link far-flung electricity supplies to demands, a smart grid needs efficient long-distance transmission. High-voltage DC power lines can efficiently transport electricity over thousands of miles, outperforming the AC lines that dominate transmission and distribution grids today [65]. DC grids could connect far-flung sources of renewable energy, allowing utilities to average out local variations in wind and solar power while bringing power to areas without much sunshine or wind. Solar power from the Sahara may power cloudy Germany in the Desertec project [66], and wind power redistributed from all over Europe could power the lights at night.

Another challenge facing the smart grid is the need to match supply and demand time profiles. Advanced energy storage is increasingly meeting that need: Fuel cells, flywheels, pumped air, pumped water, batteries, and other storage technologies are being used to distribute and level power across time and space in accordance with changing demand. Recently, the United Kingdom launched Europe's largest energy storage trial, a 10 megawatt (MW)-hour lithium-ion battery. Instead of just storing energy when it's not needed, the Smarter Network Storage project will also be used to balance the intermittency of wind and other renewables on the grid and ease capacity constraints [67]. Japan has announced a nearly $300 million grid-level battery storage project that will provide about 60 megawatt-hours to help balance solar power, expected launch in 2015 [68].

The implications of a smart grid far exceed energy efficiency or faster uptake of renewable sources. In the view of economist Jeremy Rifkin, the coming smart-grid future implies a distributed, laterally driven "energy Internet" or "Intergrid" controlled by small building-scale producers and consumers rather than centralized supplier-only utilities [69]. The role of the utility may transition from producing power to managing the power both consumed and generated by customers. Shifting to renewable energy, which is available everywhere, in contrast to fossil fuels that are concentrated in specific geographic areas of the world, further supports a decentralized and distributed energy delivery paradigm. Converting buildings into power plants with on-site generation means that the energy could be consumed locally through building, campus, or neighborhood-level microgrids, or if excess energy is produced, it could be shared dynamically with other microgrids that need it.

3.3.2 Electric Vehicles (EVs)

Increasingly, EVs are becoming nodes in the smart grid. Automotive OEMs (original equipment manufacturers) have signed agreements with the leading electric power and utility companies to prepare a new infrastructure for the plug-in transport expected to grow rapidly in the coming decades [69]. For example, GM has partnered with Con Edison in launching the Volt, and Daimler has partnered with RWE, a German power company, to establish charging points in Berlin; Toyota has partnered with EDF, France's largest utility. In turn, utilities are installing electric power charging stations along highways, in parking lots, and garages, and there is increasing pressure to develop an interconnected, big data-driven smart grid to manage the complex energy flows that result from the convergence of mobile and stationary energy. Interdependence is growing between the energy and transportation industries as the plug-in EV/fuel cell fleet grows and vehicle-to-grid (V2G) deployment increases hand-in-hand with the installation of intermittent renewable generation.

Figure 3-2. The "LEAF to Home" Power Supply System, Available in Japan [71]

A preview of the bidirectional V2G or reverse charging energy linkage can already be seen in Japan, where plug-in electric vehicles assisted in earthquake relief in March 2011. In addition to V2G systems already offered by Mitsubishi and Toyota, Nissan unveiled a new system in 2012 for drivers of its Leaf EV in Japan, which links the Leaf's DC outlet to a home's power distribution panel. Nissan claims that the Leaf's 24-kilowatt-hour, lithium-ion battery can meet the average power needs of a Japanese residence for two days [70]. (See Figure 3-2.)

In Delaware, 15 BMW electric Mini E's are being used to "balance the grid" by drawing and selling energy at appropriate times in a project led by the University of Delaware and PJM Interconnection. Each of the vehicles earns about $5 a day when the sharing system is active, or about $1,800 per year, making EV ownership financially more attractive. Instead of doing nothing while parked, a plug-in vehicle may be in continuous use as an energy storage system. According to the project lead, utilities are interested in buying electricity from groups of at least 100 vehicles. He estimates that V2G could be commercialized to a larger, multimegawatt scale in 2014 or 2015 [70].

In addition to generating and exchanging data wirelessly, data-connected EVs are becoming able to exchange energy wirelessly with infrastructure via one of a number of power transfer technologies, including inductive and magnetic resonance while either stationary or moving [72]. The necessary infrastructure to add this capability to parking spaces, bus stops, and travel lanes of roadways may limit the short-term applications to fixed routes and fleets. Stationary wireless charging for EVs in a car share is an obvious application. Hence, Hertz Corporation and Hertz Global EV are implementing what is touted as the first wireless charging system for electric vehicles in the car rental industry, called "Plugless Power" [73]. Qualcomm is running a similar wireless charging trial in London. Public transit vehicles are another rapidly growing application of wireless charging. Proterra EcoRide electric buses, already in service on several U.S. transit agencies, use wireless catenary fast-charge at bus stops to let the bus travel seamlessly along the route until a full recharge at the end of the line [74]. Nissan will soon sell an electric vehicle capable of charging wirelessly while idle in a parking lot. And at the 2011 Tokyo Motor Show, Toyota and Mitsubishi introduced an electric vehicle designed in collaboration with WiTricity, a highly efficient magnetic resonance-based wireless charging technology [72].

3.4 Summary

The essential moving parts of a smart/connected city include intelligent infrastructure, process innovations that help provide that intelligence, smart energy systems that dynamically respond to and interact with electricity loads and supplies, and, underlying it all, advanced ICT.

Table 3-2 summarizes the interacting elements that bring connected city dynamics to life, and draws out how they relate to connected transportation and what questions and issues arise as a result. Chapter 4 dives deeper into the connected transportation implications of connected city trends. Chapter 5 looks more closely at the research questions that need to be addressed as a result.

Table 3-2. Linking Aspects of the Connected City to Connected Transportation

Development	Linkages to Connected Transportation	Policy Implications or Questions
Intelligent Infrastructure: Internet of Things (IoT) and Machine-to-Machine (M2M)	Cars and transit interact with other networked devices, e.g., smartphones, streetlights, traffic control devices, building systems; vehicles can transmit information about state of infrastructure	Operations should identify how to use existing and future data streams from vehicles to identify asset problems and hazards. Need more cross-functional cooperation inside and out of State DOTs for interfacing transportation with IoT.
Process Innovation: Big Data Analytics	Predicting unsafe commercial operators; predicting crashes and congestion; awareness of traveler behaviors across all modes and of real-time travel demands	State DOTs can do more with less, targeting probable safety violators, and making more efficient use of existing transportation assets. Need to research how to leverage predictive travel demand information for dynamic demand-side user pricing. Need to break down DOT modal stovepipes to leverage mode-agnostic data streams.
Process Innovation: Crowdsourcing (e.g., Waze, StreetBump)	Superior and real-time knowledge of state transportation network; ability to influence traveler behavior in real time	Are conventional VMS and traveler information programs obsolete? Should state DOTs invest in crowdsourced issue reporting? How should THE USDOT leverage public involvement in both tool development and directing capital investment?
Process Innovation: Gamification (e.g., Chromaroma)	Travelers have new reasons and ways to use mass transit; ability to influence traveler behavior in real time; personalized traveler experience	If we can target congestion-causing travelers, how do we change their behavior to improve total system efficiency at a fraction of the cost of system expansion? How do we fund this? Need strong cross-modal cooperation to achieve multimodality, demand-side measures, and mode shift.
Smart Energy Management	Vehicle-to-grid electric vehicles will be an integral part of the electricity system; V2G vehicle locations and state of charge will be critical to plan and track	Need cross-functional cooperation with the Department of Energy and the Federal Emergency Management Agency, e.g., to integrate planning of roadway sensors, electric infrastructure, and hazard mitigation plans for power grid failures.

Chapter 4 What Roles Will Connected Transportation Play in Connected Cities?

Previous chapters have described and explained the interacting pieces that make a smart/connected city work. Armed with that understanding, we are prepared to consider what happens when they interact with each other across the various sectors of the city economy. This chapter identifies two trends that are emerging as the various sectors within a smart/connected city interact.

- **Connected Vehicles as Nodes in the Internet of Things**
  Connected vehicles of all sorts will connect numerous other data-driven systems in connected cities, presenting the possibility of new systemic efficiencies but also new system risks as well.
- **Mobility as a Service**
  The option for travelers to use multimodal mobility services in real-time—such as transit, on-demand taxis and vehicle- and ride-sharing services—to achieve the same or better mobility traditionally associated with owning a vehicle is poised to revolutionize transportation operations and planning.

Although there are many other trends that will shape the future of connected transportation in smart/connected cities, these trends appear at this point to be among the most powerful in terms of cross-sector linkages.

4.1 Connected Vehicles as Nodes in the Internet of Things

To call connected vehicles nodes in the Internet of Things is to recognize that the infrastructure of a smart and connected city is increasingly a system of systems, or a network of networks, where the networks are composed of nodes in communication with each other. Transportation systems interface with employment, residential, healthcare, utility, and city services systems, and the interface is both physical and in terms of data.

The integration of these data systems offers real promise for congestion management. In a vehicle-to-infrastructure (V2I) or vehicle-to-vehicle (V2V) system, connected vehicles will continuously broadcast location, speed, and other data. This will give traffic management systems real-time data on traffic conditions that are far more detailed and accurate than data available today. Add connected travelers equipped with smartphones to the mix, and the potential for predicting and influencing travel behavior expands dramatically.

- What if currently available smart home technology, which allows a house's energy management system to know which rooms are occupied—the bedroom versus the kitchen, as a commuter heads out to work—could provide new ways to predict travel demand by time, mode and route?
- What if transit operators could provide targeted instant electronic coupons to riders, tailored to their buying habits and personal profiles AND their transportation choices? The couponing system could drive increased ridership. The local transit agency in Montreal has begun to do just that. By pairing real-time location of bus riders with a profile of their commercial activities, the agency is able to

provide instant e-coupons as rewards for riding the bus. Retailers boost sales while the agency pursues a 40 percent increase in transit ridership [75][76].

As vehicles become nodes in the Internet of Things, not only the capacity and efficiency of the transportation network stand to benefit; situational awareness gained from communicating sensor networks has the potential to improve safety. For example, data from vehicles' external temperature sensors (common on today's cars), along with the vehicles' real-time location data, could help an operations center monitor the potential for ice on roadways at a much more granular level than is possible today. Such temperature data, combined with information on vehicle wheel slippage (as indicated by traction control systems or anti-lock brake systems being activated), would alert the operations center about the precise location of ice. The operations center could, in turn, direct deicing equipment to the exact location, and simultaneously issue an ice warning and reduced speed advisory to every vehicle upstream of the ice to reduce the likelihood of a crash.

Emerging intelligent transportation infrastructure can address transportation issues beyond congestion and safety. For example, several cities, including Los Angeles and San Francisco, are currently pilot-testing smart parking systems. These systems use networked sensors in the pavement at each parking space to monitor occupancy, and networked parking meters. Smartphone apps indicate the locations of open parking spaces to reduce the time drivers spend cruising. Such cruising constitutes a significant portion of the traffic in many downtown areas [77]. Other benefits include the ability for cities to implement variable-rate, demand-responsive parking rates [36]. In San Francisco's system, parking rates are adjusted monthly, and vary from $.25 to $6.00 per hour depending on parking demand.

Given that transportation physically connects a city's other systems to each other and is a fundamental aspect of what makes them work, the full range of potential benefits that could accrue to those various systems due to effective, data-driven integration is hard to envision. The USDOT Connected Vehicle Program has identified four functional areas where connected vehicles could help emergency operations in its bundle of Dynamic Mobility Applications entitled "Response, Emergency Staging and Communications, Uniform Management, and Evacuation," or R.E.S.C.U.M.E. In another example of cross-system integration, retailers in Montreal are using connected traveler data to reach more potential customers. What else is possible?

To achieve this promise, however, the USDOT and its partners need to confront some real non-technological challenges. Section 3.1.4 speaks to the privacy and security challenges that come with the Internet of Things. Adding connected vehicles and connected travelers to the mix will exacerbate those issues. Ensuring interoperability—allowing connected vehicles to send and receive data with the rest of the IoT—will be critical to realize benefits from integration, of course. Finally, systemic risks may arise, with increasingly interconnected data systems creating new possibilities for cascading failures.

Thankfully, there are efforts ongoing in many of these areas. The USDOT Connected Vehicle Policy Program is analyzing and developing privacy- and security-preserving options for connected vehicle technology. The USDOT is participating in machine-to-machine working groups to help ensure interoperability. On the private sector side, IBM and Cisco are collaborating on a set of device-to-device standards while competing teams are developing other standards [78][79].

Vehicles are already being sold with the capabilities to transmit data to one another and become "nodes" in the IoT. GM's OnStar was one of the first forays into connected vehicle technologies and telematics, providing users with collision detection, automatic alerts, and remote door management [80]. Many companies provide similar services, such as LoJack, Security Plus, Car Shield, and most if not all automotive manufacturers. Infrastructure technology is being demonstrated through pilot testing and will soon be proven and available for broad nationwide deployment, thus adding additional nodes. The transformation within the smart/connected city will come when these nodes are integrated and communicate with other systems in the city for mutual benefit.

4.2 Mobility as a Service

Advances in vehicle and communication technology, including connected and automated vehicles, are transforming the very concept of mobility where the emphasis is shifting to efficiently *reaching destinations* rather than committing to a particular transportation mode [81]. Increasingly, mobility will be experienced as a just-in-time service rather than owned as an asset, mirroring the embrace of software-as-a-service by many companies over the last decade, where they effectively rent data and software services via the cloud rather than purchase and manage the capability in house [82]. In the mobility space, this shift has been toward what is called “mobility on demand” [83] and “mobility as a service” [84].

Bill Ford, executive chairman of the Ford Motor Company, describes his vision for the future of mobility as “smart roads, even smarter public transport, and going green like never before” [85]. With ongoing increases in the number of cars and urbanization, he predicts “global gridlock,” and he calls for “An integrated system that uses real-time data to optimize personal mobility on a massive scale, without hassle or compromises for travelers.” Ford points to examples from Masdar in the United Arab Emirates, where driverless pod cars shuttle people around; Hong Kong, where the Octopus fare system integrates all transit modes; and of car sharing throughout the world [85]. Ford, BMW, and other automakers are increasingly labeling themselves as mobility service providers rather than as car makers, getting into new mobility business models such as car sharing, and providing mobility on-demand solutions [86]. Fleet companies are now launching corporate mobility-sharing services, even packaging Vespa-type scooters [86]. The private sector appears to be gearing up to compete in a world of “mobility as a service,” betting that it is indeed coming.

Whether one’s mobility service is provided by a car company, a rail or transit operator, airline, or bike share, seamless multimodality means on-demand access to the most immediately appropriate combination of transportation options as and when one chooses [87]. According to the World Economic Forum, consumers will increasingly seek such customized and seamless solutions to their transportation and connectivity needs in one single smartphone-type device, along with intermodal terminals and more connected networks [21].
The asset-to-service mobility shift supports and is supported in turn by three trends: the accelerating growth of:

1. Modal integration through transparent back-office data exchange
2. New mobility models such as vehicle- and ride-sharing, and
3. Smartphone apps that access open data.

The next sections discuss these trends.

4.2.1 Modal Integration

A key component of the mobility as a service vision is the ability to seamlessly access all transportation services from any origin to any destination in the most efficient way possible. As a result of growing demand for seamless multimodality, established businesses in the transportation sector are rushing to adapt. IT behemoths such as Google are entering the space, and new startups are appearing with disruptive ideas. INRIX’s Transport Protocol Experts Group (TPEG) holds that no one transportation mode can be a solution for rising pollution and congestion in an urbanizing world; rather, the solution lies in integration of multiple modes of transport [88].

Seamless multimodal travel in connected cities will depend on both integrated real-time trip planning and integrated ticketing. Already there is significant progress on both fronts, with some observers predicting fully integrated ticketing by 2025 [88]. The Integrated Proactive Intermodal Travel Assistant (IPITA) concept, as promoted by the World Economic Forum and the Boston Consulting Group, would encourage people to switch from personal transportation by car to shared-use or public transport. By reducing the complexity of coordination, users will possess real-time scheduling data, easily see travel times and costs, and use a single ticket for all the different travel modes.

There are countless examples of progress toward the ideal of seamless multimodality. Highlights include:

- In the Netherlands, the rail operator NS Business offers door-to-door mobility with a single card or smartphone app, allowing the use of rail, electric scooters, taxis, car rental/sharing, and a host of additional services, such as parking, business lounges, and even discounts for renting office space where temporary mobile working is required [86] [87].
- Deutsche Bahn's multimodal "City-Ticket" program also offers integrated transportation choices [89].
- In Guangzhou, China, the world's highest capacity bus-rapid-transit (BRT) system, the metro system, and one of the world's largest bike shares are seamlessly integrated by infrastructure and fare payment for virtually door-to-door travel throughout the metro area [90].
- North American examples are emerging as well, as VIA Rail of Canada now offers joint ticketing for rail and car-share in certain cities [91].

4.2.2 Vehicle Sharing

The advent of the Internet and wireless networks—data infrastructure connecting drivers to the (connected) vehicles they share—made the vehicle-sharing business model possible around 2000, according to Roy Russell, the founding CTO of Zipcar.

According to Kent Larson, co-director of the MIT City Science Initiative, mobility as a service implies shared-use systems [83]. Consuming anything as a service necessarily means that users share the assets, whether in space or time. Intelligent mobility (or accessibility) integrates mass transit and ride-sharing, in which multiple users share vehicles at the same time, and car and bike sharing, in which multiple users share the same vehicles at different times. Shared-use systems, like cloud computing or P2P (peer-to-peer) hoteling, mean that fewer assets are needed to meet the needs of an urbanizing population increasingly choosing to "drive light" [92]. John Markoff, a technology journalist, compares today's situation in transportation to the historic transition from the mainframe to the personal computer. "If we only need 20 percent of the cars we have," Markoff notes, "There are some really disruptive things that are going to happen" [93].

For people to be willing to share assets there must be a seamless, low-friction way to do so. The advent of the Internet and wireless networks made the vehicle-sharing business model possible around 2000, according to Roy Russell, the founding CTO of Zipcar. Easy access to vehicles depends on Internet-based reservations that can be made anywhere, on wireless networks that transmit reservation information to the car-share vehicles, and on low-cost RFID key technology. A vehicle-sharing business simply could not have been built in the 1990s [94]. Since that time, the availability of smartphones, apps, and GPS has continued enabling ever more sophisticated and easy-to-use business models for vehicle sharing by making it even easier and more frictionless to use.

4.2.2.1 Car-Share Business Models

Car sharing is becoming an increasingly important model, with a customer base that has grown 40 percent annually over the past decade [95]. There were 1.7 million car-sharing members sharing over 43,550 vehicles in 27 countries in 2012 [96], not including the peer-to-peer services that allow drivers to rent vehicles directly from individual car owners [97]. The trends are similar in the U.S., which is home to 800,000 car-share members in 2012, a 44 percent increase from 2011 [97]. Zooming into the city level, Washington, DC, shows the same pattern. Since its establishment in the fall of 2001, Zipcar DC grew to over 60,000 members and 900 vehicles in 2012 [98]. Similarly, during the first year of Car2Go DC 19,000 members signed up and 350 vehicles were operational [99]. According to Frost and Sullivan, an additional 4.4 million people in North America and 5.5 million people in Europe will sign up for services like the one from Zipcar over the next five years. Projections by Navigant Research show global car-sharing services revenue increasing from $1 billion in 2013 to $6.3 billion by 2020 [100].

Vehicle-sharing business models allow users to rent vehicles by a range of times, giving them access to mobility without sunk ownership costs. With most of the services, customers make reservations over the Web or with a smartphone app, and rates are usually by the hour [97]. The conditions for successful traditional car sharing include sufficient residential density, organic network growth outward, and proximity to mass transit [96]. These are the same principles as for bike-share systems, which have also experienced rapid growth since the mid-2000s [95]. However, new business models are proliferating and now include university and corporate fleets, automotive OEM-run services, peer-to-peer car sharing, and one-way car sharing [100].

The various vehicle-sharing systems, for both bicycles and cars, can be categorized by two key metrics: centralized versus P2P, and round-trip versus one-way—see Figure 4-1.

In centralized systems, the vehicle fleet and associated infrastructure are owned and maintained by a single entity, such as Zipcar, Velib, CitiBike, Autolib, or Car2Go. In P2P or distributed services, the fleet is owned by many individual owners. Transactions are mediated by services such as Buzzcar, RelayRides, FlightCar, Getaround, and Spinlister, allowing car or bicycle owners to rent their vehicles to other people in discrete increments of time. The friction or transaction costs in P2P systems are still higher because of the need for face-to-face interaction. In the not-too-distant future, however, P2P car-share platforms will likely offer the same secure, reliable, low-friction access that centralized car-share systems already provide, thanks to cheap mobile technology. Because monetizing the enormous excess capacity of private cars (95 percent of their lifetimes) would be highly scalable, P2P has the potential to be highly disruptive in replacing longer two-way trips that today are made by private car and traditional rental cars [94]. Companies like Uber, Lyft and Sidecar have capitalized on P2P car-sharing models.

By way of example, Uber's business is based on using cellular technologies to enhance passenger carrying operations. The cellular application connects riders with local drivers, allowing for real-time service that is paid for wirelessly. In this model drivers are considered independent contractors and responsible for their own maintenance, insurance, and car fees [101].

Founded in 2009, Uber is the largest car-sharing company in the world, and its success has made it the focus of regulatory discussions. The main argument is that, despite its novel business model, Uber is essentially providing taxicab services—rides for a fee. It presents the same risks to the traveling public as does a traditional taxi company, according to the argument, and the government therefore has the same responsibility to regulate it in terms of driver background checks, vehicle inspections, and insurance [102]. Critics following this logic contend that the fact that Uber is not regulated in the same way gives it an unfair advantage. For example, in Chicago, taxicab drivers must pay between $325,000-375,000 for a medallion that certifies the vehicle and acts as a contract between the vehicle owner and the city [102].

To address the above concerns, some cities such as Seattle and Minnesota have changed legislation to accommodate the P2P car-sharing model. *The Washington Post* recommended nine areas to analyze while making car-sharing policies to create a fair passenger carrying environment: the number of hours Uber drivers operate, more detailed/ complex background checks on Uber drivers, proper insurance requirements, demand based pricing, Uber driver training, Uber drivers' licenses and renewal processes, Uber vehicle inspections, Uber driver check-ins and a standard pricing scheme [103]. Uber and other companies in the sharing economy, such as Airbnb, are confronting similar challenges in regulatory flexibility, and there is every indication that work in this area—by governments, academics, and the businesses themselves—will continue [104].

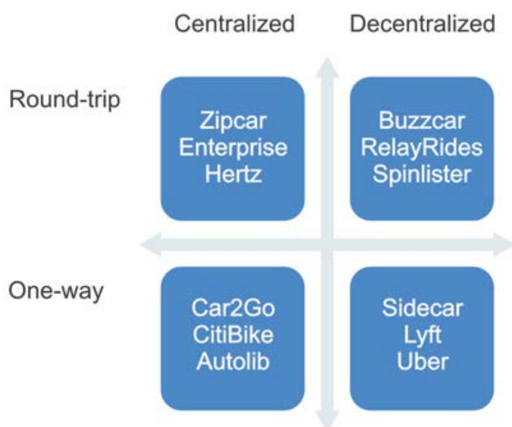

Figure 4-1. Taxonomy and Representative Examples of Vehicle-Sharing Services

4.2.2.2 Bike Share

Most car-share systems, including industry leader Zipcar, require users to return vehicles to their origin at the end of the trip. However, bike-share systems have provided one-way vehicle-sharing service from the start, and they have "experienced the fastest growth of any mode of transport in the history of the planet [105]." In these systems, bicycles may be checked out of any docking station and returned to any other station within the system. Bike shares combine the one-way service of mass transit or taxis with the full connectivity of the city road network. Much as car sharing would not have been possible without advances in ICT over the last decade, modern bike sharing only became possible with wireless Internet connectivity and low-power electronics powered by small solar panels on the bike-share stations; smartphone apps are further enhancing bike-share's reach and effectiveness. In just over a decade, the public bike-share coverage worldwide has swelled to about 500 cities in 49 countries [106]. At the start of 2013, the U.S. was home to 22 modern public bike-sharing programs with 17,000 bikes. By spring 2014, that number will likely double and continue rapid growth [107]. Capital Bikeshare in Washington DC, launched in 2010, is a case in point. In its first year of operation, it enrolled 18,000 members, with that number exceeding 22,000 by the end of 2012 [108][109].

The experience in Paris suggests the possible impact of bike sharing at a large scale in the U.S. In Paris, a 21,000-bicycle system called Vélib' has increased bicycling volumes by 70 percent since it was introduced in July 2007, and the system is credited with reducing Paris traffic by 5 percent in its first year [110]. Suggestive of such eventual impact in the U.S., 43 percent of Denver B-Cycle users report replacing car trips with bike rides [111], and 20 percent of trips on Minneapolis' Nice Ride were substituted for motor vehicle trips [112].

According to an Earth Policy Institute compilation, tens of thousands of bike-share vehicles are either deployed or planned for deployment in the U.S. within the next few years. See Figure 4-2.

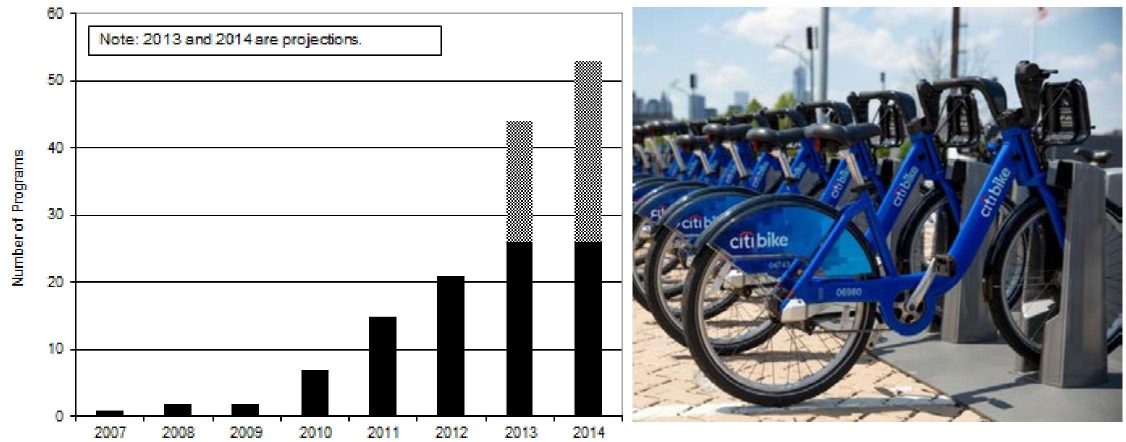

Figure 4-2. Bike Share: Public Programs in the U.S., 2007-2014 [106]; Example of a Station in New York City [113]

4.2.2.3 New Players, Rapid Growth

Taking a cue from one-way bike-share systems, entirely new types of one-way car-share services are rapidly emerging as well. Services such as Car2Go and DriveNow are already in service in continental Europe, Canada and the U.S. Daimler has stated that its Car2Go unit emerged from a business innovation group that projected the future of city transportation. The mobility service, which has reached financial break-even points in three cities, launched in Europe and now has about 275,000 members worldwide. The service charges customers by the minute instead of the hour, allows for one-way rentals, and includes street parking within a defined urban boundary [97]. Figure 4-3 shows Zipcar and Car2Go vehicles.

Cities benefit from vehicle sharing due to a reduction in the number of private cars, the total VMT, and the land devoted to parking while car-sharing users are reported to save about $5,000 per year by substituting car-share membership for car ownership [94]. Not surprisingly, major car rental agencies and carmakers are developing their own programs in this area [114]. For example, auto-rental company Hertz is expanding its presence in the car-sharing sphere by making 500,000 vehicles in its global fleet accessible for short-term rentals [115]. At that point, Hertz 24/7's fleet will be more than 10 times the size of the current car-sharing industry combined.

Figure 4-3. Zipcar Two-Way Car Share (left) [116] and Car2Go One-Way Car Share (right) [117]

According to a 2012 Royal Automobile Club report, the expected two-way traditional car-share market in London is over 400,000 active subscribers compared to just over 100,000 today. More strikingly, the market size is 1.5 million subscribers for a prospective one-way system in Greater London—15 times higher than current car-share membership [94]. If the car-share market potential in U.S. cities were comparable to the London figures, then today's 800,000 U.S. subscribers could grow to 12 million with the advent of one-way systems in cities already serviced by traditional car sharing. That would comprise about 5 percent of all licensed drivers in the U.S. Automobile ownership rates in car share cities range from 70 percent of households in Pittsburgh to only 44 percent in New York City [118], and according to Frost and Sullivan, each shared vehicle displaces about 15 personally owned vehicles [94][119]. Thus the existing U.S. car-share population has already removed 225,000–300,000 cars from U.S. roads. By extrapolation, some 4.5 million private cars could be removed from U.S. cities in a one-way car-share future, or even more if Hertz's car-share plans are fully realized.

At present, vehicles in car-share fleets are typically standard models that have been fitted with aftermarket telematics. In contrast, bike-sharing systems use purpose-built bicycles. Car models such as the Car2Go Smart Cars that are built specifically for car-share operations are expected to proliferate [95]. As more automakers design purpose-built shared vehicles, they will bring down the cost of embedding sensors and transmitters for onboard telematics. This will expand car share and also support smart/connected city infrastructure by making it possible to exchange data about air-quality, vehicle speed, road condition, and more with the surrounding intelligent infrastructure.

4.2.2.4 Ride Sharing

App-based ride-sharing platforms are increasingly pairing travelers with like-minded people traveling to similar destinations on the same schedule. Like vehicle sharing, the business models have only recently become possible with developments in ICT, specifically widespread mobile Internet access that provides real-time GPS location and availability data and facilitates cashless automatic payment. In ride sharing, there is no meter; the driver uses the GPS in a smartphone to calculate the fare, and passengers are seamlessly billed when the trip ends. Users can also rate the ride, write reviews, or request future rides with the same driver.

Because no driver's license or driving ability are required for the ride-share user, ride-sharing offers even broader and more spontaneous access than car sharing, with the same ability to multitask as when using transit or traditional taxis. Despite protests from the incumbent taxi industry, tech-savvy drivers and passengers are rapidly embracing the ride-sharing model [120]. Lyft and Sidecar are among the most widely used platforms. Within its first year of operation, the ride-sharing service Lyft served over 1 million riders among more than 100,000 registered users [121], while SideCar has facilitated more than 150,000 P2P rides, and Uber already operates in 35 cities and has been valued at nearly $3 billion [122]. Sidecar most closely aligns with the capture of excess car capacity, while Uber operates like a streamlined shadow taxi fleet. Sidecar users must specify both the origin and desired destination to be matched with nearby drivers with available seats that are already traveling in the same direction.

4.2.2.5 Emerging Transportation Modes

In addition to sharing existing transportation modes as discussed above, industry groups and observers foresee new modes entering the mix. Citing forecasts that 60 percent of vehicles by 2017 will be connected vehicles (versus 11 percent today), and that there will be 5 billion smartphone users by 2020, Ryan Chin of

MIT asserts that an Autonomous Mobility-on-Demand (A-MoD) network of driverless “swarm cars” will work in conjunction with public transit systems to solve the complete accessibility and mobility puzzle, including the first-mile/last-mile challenge of bridging the gap between transit stops and final destinations. Mirroring similar predictions by the World Economic Forum, this network of automated vehicles would essentially act as driverless taxis [114]. Intelligent demand predictions would steer cars to where they are needed, with idle time used for last-mile logistics services or at wireless charging stations [21].

Other possible new transportation options that may penetrate the mix within 10–25 years include Toyota’s version of the Segway personal mobility device, the Winglet [123]. In the air, logistics drones and smaller commercial heli-drones may begin to make deliveries within congested megacities. These unmanned aerial vehicles (UAVs) could become integral parts of our freight and logistics networks in the future [124]. Indeed, the Federal Aviation Administration is likely to open up domestic airspace to large drones by 2015 and expects 10,000 unmanned commercial aircraft to be operating by 2017 [21].

Given the possibility of 2.5 billion cars on the planet by 2050, Ryan Chin emphasizes that sustainably low-energy transportation will require more walking, biking, and smarter mass transit, and not mass motorization. What is also clear is that online retailing will continue to grow and therefore displace personal travel to stores. E-commerce will exceed 20 percent of U.S. retail sales by 2020 and 30 percent by 2025 [21], leading to increasing urban freight volumes and increasing the pressure to develop seamless, last-mile urban-delivery solutions [86].

4.2.2.6 Mobility Apps

Following Google’s purchase of Waze, there is significant attention paid to real-time, smartphone-based transportation management schemes. Investment in intelligent traffic management systems, part of the larger connected cities movement, is growing. Smartphones with GPS location awareness have made new transportation businesses possible and have accelerated the shift to mobility as a just-in-time service rather than a fixed-cost asset. At the same time, growing amounts of data produced and transmitted by the onboard computers in connected and automated vehicles will soon feed larger quantities of real-time data into mobility apps.

The most visible manifestation of mobility apps are the ride-sharing platforms, such as Sidecar and Lyft. But the extent and impact of ubiquitous, real-time, location-aware navigation and ticketing at the tap of a touchscreen extends much farther. In addition to P2P services, established taxis can now be easily requested via smartphone, increasing their utilization and reducing their empty cruise time [125]. Car drivers seeking metered street parking can increasingly find available spaces in real-time with smartphone apps like SFpark [126] and pay for them using apps such as PayByPhone [127] and ParkNOW [128]. And as discussed in section 3.2.2 ,Waze provides a community of tens of millions of users’ crowdsourcing real-time traffic, map-route and gas-price information [57].

Perhaps most indicative of the emerging seamless multimodalism are platforms such as CityMapper, TransitScreen, and RideScout. RideScout describes itself as a “mobile application that aggregates ground transportation ride options to allow users to compare them in real time” [129]. Even for people who are not accustomed to using non-automobile transportation modes, the emergence of multimodal navigation apps (and eventually ticketing apps) makes it is easy to figure out how to combine once obscure transit networks and bicycle routes. Hundreds of smartphone apps now use GPS data to indicate in real-time which bus or subway a traveler should choose, when it will arrive, where to get on, where to get off, and other information to make the trip increasingly effortless. As one resident of Charlotte, NC who used to drive to work but switched to a mix of biking and mass transit options said, “You don’t have a lot to figure out. We all have navigators in our pockets” [130].

Even companies that have traditionally identified themselves as automakers are entering the multimodal mobility app arena. BMW has launched a series of urban mobility services under the umbrella of “BMW i Mobility Services,” including an app called Embark that has real-time information on 12 major public transit systems in the U.S. and the United Kingdom [131]. Daimler has launched an app in Germany called “moovel,” which shows the various options for bus and rail connections, ride-sharing opportunities and a taxicab call function similar to the app Hailo.

4.2.3 Summary

Connected transportation will interface with other systems in connected cities in at least two fundamental ways. First, as they become ubiquitous, connected vehicles and connected travelers will serve as the data exchange points feeding transportation system data to the other systems—healthcare, utilities, employment, retail and entertainment, residential, and public services—and receiving data from them as well in a smart/connected city. This opens the door for innovations in service delivery and business and agency operations that are difficult to foresee. Second, connected transportation has begun and will continue to facilitate a shift in transportation consumption. The shift is from making a long-term commitment to a particular mode or modes of transportation, and toward being able to make near real-time decisions about what mobility services to use.

Chapter 5 Conclusions and Recommendations

Connected vehicles will be deployed in smart/connected cities. Smart/connected cities are effectively systems of systems, including employment, health care, public services, retail/entertainment, and transportation. As the data-linked parts of the transportation system, connected vehicles will be interfacing with the other systems in the smart/connected city. This presents opportunities for cross-industry coordination that have yet to be identified or realized.

To take the next step in defining and exploiting these opportunities for synergy, recommended research questions include the following:

- What are the **critical issues and challenges facing today's cities**? How can connected vehicle technologies, data, and applications help address these issues?
- How will the integrated and connected nature of today's cities be of critical importance to the **likelihood of success of the eventual deployment of connected vehicles**?
- How do **transportation services and connected vehicle technologies, data, and applications intersect with other sectors of the economy** (i.e., energy, telecommunications, public safety, public works, public transit, logistics, industry, public health, retail, etc.) and how can these sectors **leverage technology** for the overall benefit of a jurisdiction?
- How can connected vehicle data—along with transportation data and other data available in a smart/connected city—be used to create **innovative and informative real-time visualization techniques to support decision making** by public agencies and connected travelers? What are the most effective and innovative real-time data visualization techniques for transportation decision making by public agencies and connected travelers? Who is doing state of the art real-time data visualization—both in transportation and in other sectors? What products and associated trends are resulting from these efforts?
- What **data gaps** exist in cities? Are there data a city wishes it had that connected vehicles can provide? From what variety of sources can transportation data be collected? What technologies and methodologies are most useful for doing so? How can all these **data be efficiently managed, used and re-used, in a smart/connected city**? What other sectors might benefit from connected vehicle data? How might the transport sector benefit from data from other sectors?
- What types of **crowdsourcing, social media, gamification, and incentivization strategies** can be used to effectively address/solve transportation issues in a smart/connected city? Are some strategies or techniques more effective than others when desiring a certain outcome, objective, or result? What are their limitations? When are they most useful? How can they become effective decision support tools—not only for real-time needs, but to meet longer-term public policy objectives and perhaps even instigate social/behavioral change over time?
- How will the **expanding market for electric and alternative fuel vehicles change the mobility landscape in a city**? Change the expectations of drivers? Affect tax revenues of cities and states?

Influence the market for shared-use mobility? How will connected vehicles interact with the **smart grid and the cloud**? How will they interact with electric vehicles? How can the operational characteristics of electric vehicles be integrated into connected vehicle applications?

- What are the implications for connected vehicles with respect to **shared-use mobility**?
- How can connected vehicle data be used to support smart/connected city performance metrics? What **metrics and indicators** are most valuable for the transport sector to measure and monitor in the future if a city is well-integrated and connected?
- What is the role of **predictive data and analytics** in a smart/connected city? How is predictive data developed within the transportation community using connected vehicle data? How can predictive data be used effectively to support transportation operations in a smart/connected city? What other sectors might be interested in using this data?
- Who are the **core stakeholders** at the nexus of the connected traveler and the smart/connected city, both inside and outside of transportation? How can necessary partnerships and other relationships among them be developed?
- What cities or jurisdictions are **likely candidates for partnering** with the ITS JPO to explore these themes further in the context of anticipated connected vehicle deployment?
- What **institutional barriers** might hinder the implementation of connected vehicle-based, integrated city solutions? How can these barriers be overcome? Which cities have overcome these challenges? What were critical success factors? What institutional barriers exist that may prevent connected vehicle data from being accessed and/or integrated with other data sources in cities to meet transportation and mobility needs?
- How are planning agencies harnessing the potential of connected vehicle data, and supporting smart transportation applications in the traditional **transportation planning process**?
- With **limited funding** sources available, are transportation agencies finding ways to cost-share to implement smart solutions that utilize connected vehicle data? If not, what practices can the ITS JPO promote to ensure connected vehicle data is easily available for use by other agencies in a smart/connected city? Are there examples of public-private partnerships where smart vehicle data is being used?

Questions like these and others will continue to emerge. To organize a path forward and inform the development of a research agenda, the research team proposes the following eight objectives.

1. Identify how cities (of all sizes) and city agencies (of all types) can harness the power and potential of connected vehicle data, technologies, and applications—and leverage these effectively and efficiently to help achieve mobility, economic, social, and other goals.
2. Explore how cities and city agencies might leverage the opportunities presented by Internet-connected mobile communications technologies—and the data they collect and generate—to connect to citizens, influence traveler behavior in the short and long term, and affect public policy and decision-making.
3. Identify the implications of shared-use mobility, mobility-on-demand, and mobility rightsizing on driver behavior and the changing socio-economic views of driving and mobility.
4. Identify how connected vehicle data can be integrated with a wide variety of other data to create the most effective, innovative, and informative real-time (and predictive) data visualizations to support effective and efficient decision making by a variety of public agencies and also by connected travelers.

5. Identify the most effective crowdsourcing, gamification, and incentivization strategies and applications to address and solve transportation issues/problems and explore how connected vehicle data, technologies, and applications can contribute to support agency and traveler needs.
6. Identify how electric and other alternative fuel vehicles will (or will not) affect mobility decisions in the future (including the economics and purpose of driving), and how these changes might affect the deployment of connected vehicle technologies and applications.
7. Evaluate the benefits of connected vehicle technologies and applications at three levels–overall societal impacts, advancement of cities' particular missions, and personal financial savings—within an overall framework of integrated city activates and services.
8. Identify core stakeholders/partners in the public and private sectors to develop strategies and best practices to leverage connected vehicle technologies, data, and applications, and push forward the state of the practice and the state of the art.

The research team anticipates that USDOT will work with traditional transportation partners and reach out to representatives to validate the objectives and seek input on the questions. The ultimate goals of federal research in this area are to advance the state of the practice in connected transportation and foster the institutional cooperation that will help realize the full potential of emerging connected vehicle technologies within the smart/connected city environment.

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APPENDIX A. List of Acronyms

FTC	Federal Trade Commission
GE	General Electric
GPS	Global Positioning System
ICT	Information and Communications Technologies
INROADS	Intelligent Renewable Optical Advisory System
IoT	Internet of Things
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
ITS JPO	Intelligent Transportation Systems Joint Program Office
LED	Light-Emitting Diode
M2M	Machine-to-Machine
MAC	Media Access Control
MIT	Massachusetts Institute of Technology
MW	Megawatts
NFC	Near-Field Communication
OEM	(Automotive) Original Equipment Manufacturer
P2P	Peer-to-Peer
RFID	Radio-Frequency Identification Device
SQL	Structured Query Language
UPS	United Parcel Service
USDOT	U.S. Department of Transportation
V2G	Vehicle-to-Grid
V2I	Vehicle-to-Infrastructure/ Infrastructure-to-Vehicle
V2V	Vehicle-to-Vehicle

APPENDIX B. Glossary

Big Data
A family of data management and analysis techniques necessary to draw insights from huge volumes of diverse data.

Cloud Computing
The process in which networks of physically separate devices are connected via a network to provide capabilities that would previously have been provided by a single computer.

Connected Transportation
Transportation in which vehicles, travelers, and infrastructure communicate with each other through various data streams.

Crowdsourcing
The practice of obtaining needed services, ideas, or content by soliciting contributions from a large group of people and especially from the online community rather than from traditional employees or suppliers.

Gamification
The application of game design principles to non-game activities, incentivizing user engagement by appealing to a sense of fun and competition.

Information and communications technologies (ICT)
Technologies that transmit and process data about various systems within a city.

Internet of Things
A concept that built infrastructure is linked and dynamic, often displaying intelligence via integrated sensors and adaptive controls.

Intelligent Infrastructure
Devices and equipment that can sense the environment and/or their own status, send data, and often, receive commands.

Smart Grid
A programmable and efficient electricity transmission and distribution system that responds to dynamic electricity demands.

Smart/Connected City
A city of interconnected systems (employment, health care, retail/ entertainment, public services, energy distribution, and transportation) tied together by information and communications technologies.

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